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SPACE-BASED E-TEXTILE ARRAYS

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Abstract: Next-generation space-based radar and communications arrays require very large apertures in order to achieve the required gain and resolution. The implementation of these very large apertures poses several challenges in order to reduce the cost and weight while improving manufacturability. As system requirements have grown more stringent and required arrays have increased in size, new forms of antenna implementation are desirable. Electronic textiles, or E-textiles, is a candidate new technology that promises lighter weight and lower cost flexible options for satisfying a wide range of array applications. In this paper, we discuss the design of an L band array partitioned into subarrays to realize a total aperture of more than 100 meters in length. Multilayer designs utilizing embroidered antenna patches, knitted polyester spacers and woven ground planes are examined. We discuss the requirements for building a one meter by one meter subarray panel for a precision radar demonstration prototype. Array issues including subarray partitioning, beamwidths, beamsteering, antenna manufacturing tolerances and material electromagnetic property variations as they affect the final system performance are addressed. We summarize by showing that significant array advances are feasible and illustrate the development challenges that this technology faces.

1. Introduction

Early radar satellites were deployed in a variety of LEO orbits at altitudes of less than 1000 km [1, 2]. As the throw weights of launch vehicles has increased and system requirements have become more demanding, satellites are being deployed in MEO altitudes to 10,000 km. These higher orbits require larger antenna apertures to maintain system capabilities [3]. For example, an aircraft surveillance radar with a seven meter aperture has been projected to translate to a 57 meter aperture for a LEO orbit satellite of the same capability and to a 320 meter aperture for a MEO orbit [4]. The manufacturing of very large aperture antennas within realistic cost and weight constraints is a very challenging problem. There

have been several technologies suggested for implementation. These include inflatable reflector antennas [5] and extensions of conventional printed microcircuit antennas. Another technology that has significant cost and weight advantages over conventional plated microcircuit technology is Electronic Textiles or E-Textiles [6]. The application of this technology to space-based arrays is therefore being investigated. In our paper we first review the impact of higher altitude orbits on the size of the deployed arrays. We then seek to simplify the implementation of these arrays through the use of subarray beamforming. We use several examples to establish the context for real radar and communication applications of our array technology.

In section 3, we review the patch level technology that has proven feasibility. Here a key aspect is to transition from hand constructed antenna prototypes to an automated, computer controlled manufacturing process that produces a predictable, high performance product. In section 4 we cover current progress in developing a one meter square subarray that can enable space-based large aperture deployments.

2.0 Space-Based Very Large Aperture Radar Ranging

Previous earth satellites employed for radar surveillance purposes have utilized LEO orbits. For example, the Seasat and RadarSat satellites as well as the envisioned Space Based Radar and TerraSar satellites all employ orbits with heights of less than 1000 km. However, future missions will employ higher orbits to reduce the number of system satellites, to simplify control and orbital maintenance and to improve mission flexibility and performance. For these missions, orbital heights of from 1000 to 10000 km are planned. Missions include both radar surveillance and communications relay objectives. One of the most important contributors to the success of these missions is the availability of larger, low-cost, lightweight antenna apertures to support the more stringent beamforming and beam pointing requirements.

To extrapolate aperture performance to other ranges, we can employ a simplified model of satellite-based illumination and use the equation,

$$X_{cr} = (\lambda/D_{aperture})*R, \tag{1}$$

where X_{cr} is the desired cross range resolution, $D_{aperture}$ is the aperture length, λ is the wavelength of the radar or communication system and R is the distance from the imaged surface to the imaging radar. Using this equation, we can see that

a radar that has a cross range illumination of 600 meters at a nominal 10 GHz using a 10 meter aperture at an altitude of 200 km will require a 100 meter aperture at a range of 2000 km. These are large apertures but we note that radio astronomy routinely uses even greater apertures so the issue is how to build and deploy these large antenna arrays in space.

Another significant determinant of array construction complexity is the feed network that connects the array antennas with the system transceiver. Note that this transceiver can in fact be composed of a multiplicity of transceivers where each transceiver may be connected to only a portion of the total number of array antennas. For comparison purposes, we consider here the single transceiver case and examine the use of subarrays to simplify array construction. If a single array consisting of N_e antenna elements is connected to an analog summation beamformer, then a single aperture with an angular resolution of φ is formed where $\varphi = \lambda/D_{aperture}$. If this same array is divided into two nonoverlapping subarrays each of which incorporates a separate analog summation beamformer, then the outputs of these two subarrays may be steered to cover a field of view that to a first approximation is equal to $2*\varphi$. Likewise, if the array is divided into N equal, separate subarrays, then the field-of-view is approximately $N*\varphi$. When the array consists of N_e individual steerable antenna elements, then the full field - of-view of 120 to 180 degrees can be scanned electronically. The subarray beamformers may be digitally switched phase shifters or they may be fully digital and implemented in the time or the frequency domain. Of importance to E-Textile array construction is that the additional subarray beamformers can lead to a less complex implementation so that the total field-of-view to be scanned is an important design variable.

The total field-of-view is dependent on the mission that the array supports [7]. For an earth surveillance satellite, a fixed aperture that is scanned across the earth by the motion of the satellite may be sufficient. Any greater resolution than that provided by the real physical aperture may be provided by introducing a phase stable correction and synthetic aperture formation. However, in the case of spot beam radars or communications systems, a single beam covering the entire area of interest may not provide a sufficient SNR. Spot beam steering is then required. Earth coverage from an orbital height of 2000 km requires a total scan capability of about 100 degrees while scanning from 20000 km requires a scan of about 28 degrees. For comparison, a satellite could operate from a geosynchronous 35,784 km orbit where the total earth coverage scan would be approximately 18 degrees. It can be seen that since the field-of-view of higher orbit satellites is less than that

of LEO satellites, the use of subarray beamforming to reduce the complexity of an array implementation becomes more important. We are therefore including the use of subarrays in our investigations.

A prototyping benchmark is necessary is focus our development efforts and to provide tradeoffs that will lead to deployed systems. A reasonable array size, compatible with early large aperture array requirements incorporates a 100 meter aperture divided into individual one meter square subarrays as shown below. The initial design frequency of operation is 2.435 GHz. This frequency was chosen so that early implementations would be tolerant of textile fabrication tolerances. The implementation of the one meter square subarrays enables those subarrays to use additional, smaller subarrays to meet system requirements in an efficient manner.

3. E-Textile Patch Antenna Technology

In assembling larges subarrays from individual patches we rely on an established hierarchy of textile industry fabrication [8], [9]. This hierarchy considers fibers to be the first and fundamental material from which threads, yarns and rope are made. The threads and yarns are then woven or knit into fabrics which are quasi-planer; that is, they have a significant thickness but are generally produced as flat or sheet goods. From the fabrics, finished products such as garments are produced through a process that incorporates cutting, stitching, gluing and coating. It is also true that more recent processes construct nonwoven fabrics directly from the fibers and binder materials. We note here that every level of the product construction process, from the fiber level to the garment level, can be used for electronic textile antenna construction. The most advantageous selection of available methods and the integration of these methods into the best antenna construction process is the subject of our current research.

To explore E-Textile antenna construction methods, we first designed a prototype antenna patch. The top view of the patch antenna is shown in Figure 1. The design of this patch is based on a transmission line model in which the energy is transferred from the feed point to free space radiation. There are three stacked E-Textile patch antenna elements - a ground plane, a spacer layer and a conductive antenna patch Energy is radiated in transveral mode. To effectively radiate, the antenna is impedance matched to the drive line through a microstrip transformer which consists of a thin patch that connects the bonding pad to the antenna patch.

The usual construction method is to employ a sandwich of two copper layers bonded to a high performance microwave substrate such as Rogers 5880. One of the copper layers is then etched to form the antenna patch. This form of construction produces a heavy, rigid, planar patch antenna. Such an antenna has limited potential to our space-based antenna array objectives. However, it is a current standard because precise construction techniques are available that produce predictable performance.
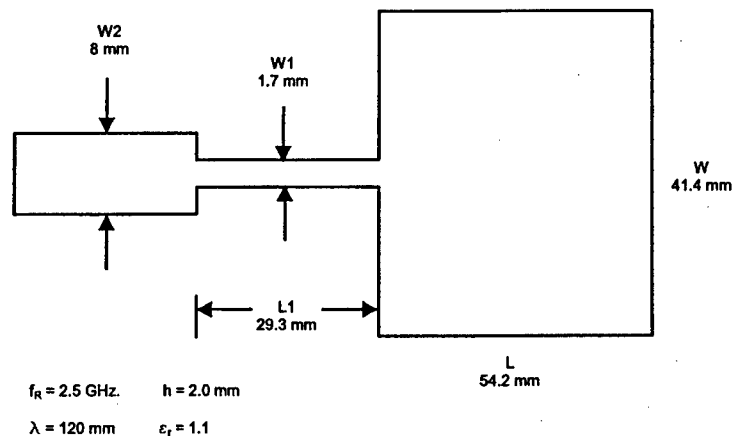
W2
8 mm

W1
1.7 mm

W
41.4 mm

L1
29.3 mm

L
54.2 mm

f_R = 2.5 GHz.   h = 2.0 mm

λ = 120 mm ε_r = 1.1

Figure 1: Microwave Patch Antenna Design

We have investigated several alternative E-Textile patch construction methods. These were in two classes of material composition. The first was consists of flexible antennas assembled from fabric components. The second were fabric component antennas which were assembled into rigid structures using epoxy resin. A total of eight patch antennas and several prototype transmission lines were constructed. These transmission lines constitute an RF interconnect. We focus on the antennas shown below.

There are at least two methods of constructing E-Textile antenna patches. The first method is to weave, sew or embroider the wire or conductive yarn into the fabric. We conducted numerous experiments in sewing and embroidering wire. Initial experiments utilized patterns of wire sewn by hand into a fabric. Using this process we stitched antenna patches into a flexible nylon fabric (Figure 2a) and vinyl upholstery fabric (Figure 2b) and (Figure 2c). We found that these fabrics were dimensionally stable even when tensioned and they did not tear away from

the wire when flexed. For spacer materials we used urethane foam and several knit spacer fabrics. Finally, we used both copper cloth and copper polyester tape
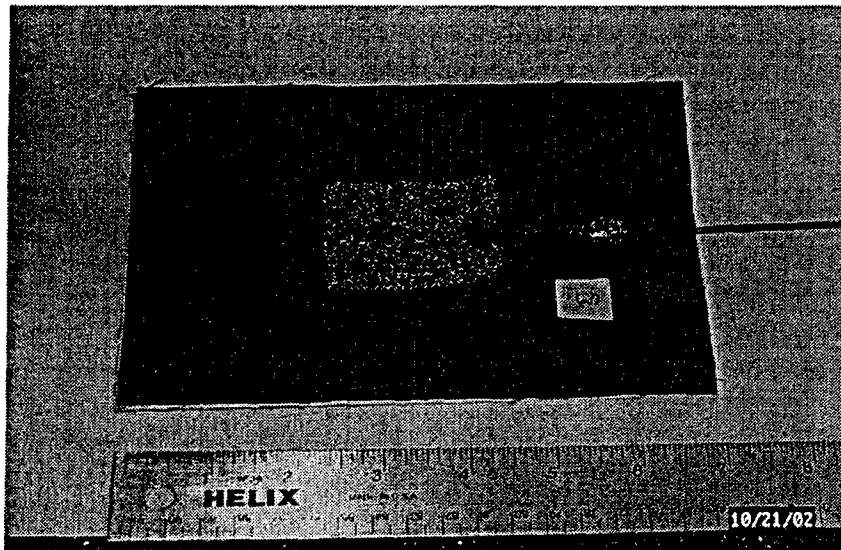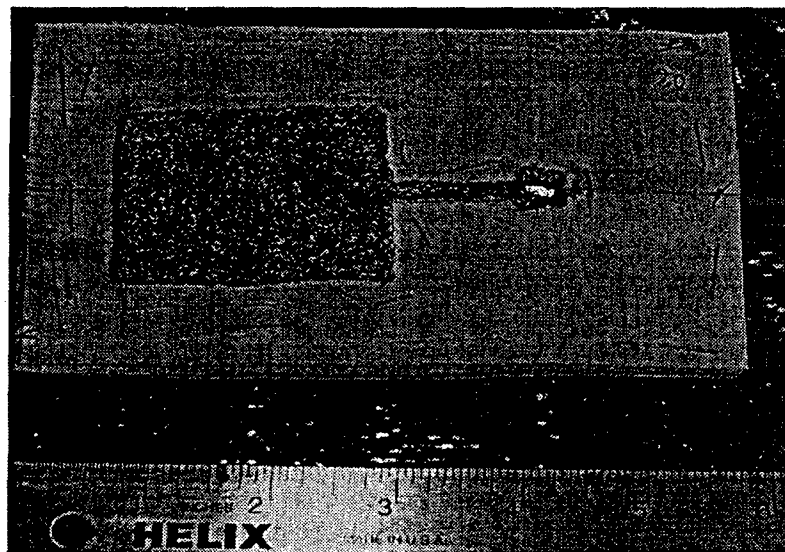

Figure 2a: E-Textile Flexible Patch Antenna

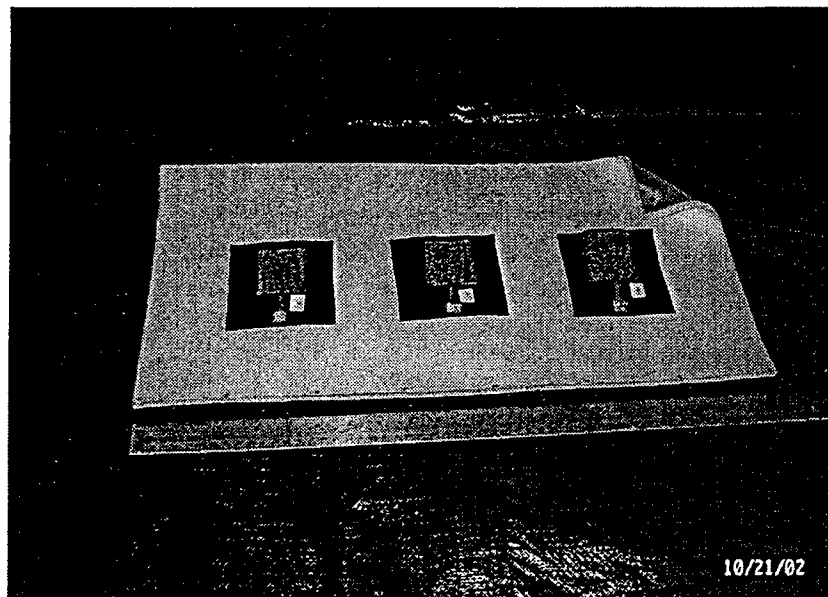Figure 2b: Foam and Vinyl Sandwich Antenna

Figure 2c: Multiple Patch Antenna Array

materials for the ground plane layer. These layers were then stitched together with very light thread tension so that the antenna was not distorted. The microwave feed was thin coax which was attached to the stainless steel feed pads. We have also constructed a preliminary three patch array prototype by stitching three patches onto one textile substrate as shown in Figure 2c.

A second method of antenna construction attaches a wire antenna patch made of copper cloth onto a fabric. The patches are cut out of conductive cloth and sewn onto the carrier fabric. We have constructed experimental prototypes by cutting antenna patches out of copper wire cloth and then sewing these patches onto heavy nylon fabric. The dimensional tolerances that can be held with this method may exceed those possible with the wire sewing method. Since the sewing process is so precise with preassembly cutting and since a lock-stitch machine can be used to attach the patch to the fabric, the manufacturing yield of this method is greater than with the wire sewing method. However, the antenna is less integrated with the host fabric and possibly more subject to degradation upon flexure and abrasion. An example of an antenna patch sewn by this method is shown below in Figure 3.

As mentioned above, the fabric antenna patches can be incorporated into composite structures. We produced two patch antennas using stainless steel wire embroidered into heavy (36 and 24 Oz.) industrial grade fiberglass. This fiberglass is used to make airplane fuselages and boat hulls. The ground plane was a graphite fabric and a honeycomb spacer layer was used. This spacer is rigid and the entire composite structure is rigid and load bearing when completed. We believe that the over stitching method of patch incorporation has promise here as well. The inclusion of graphite ground planes and wire antenna structures may be compatible with the structural requirements of several spacecraft.
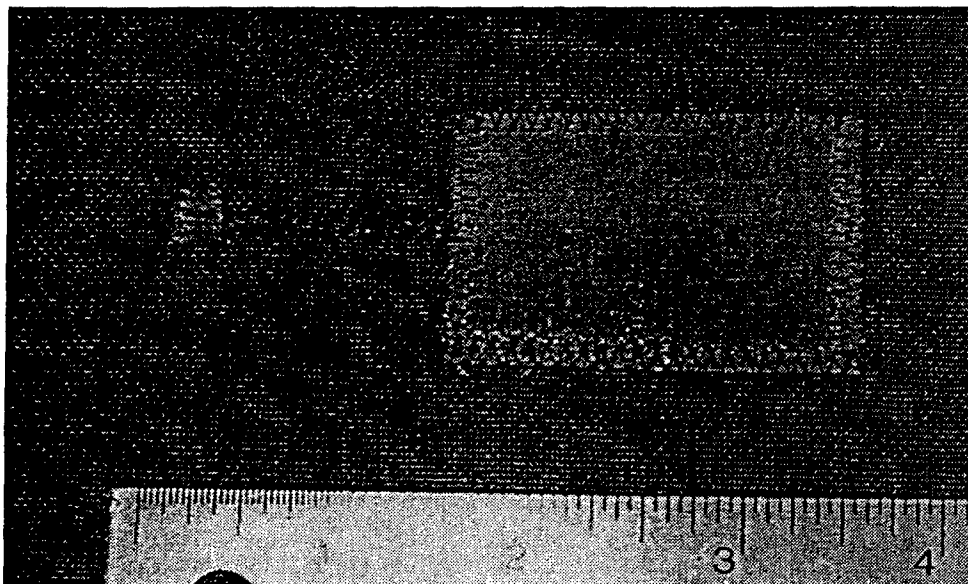

Figure 3: Copper Cloth Antenna Patch Stitched Over Fabric

4. Space-Based Subarray Design

To design a full subarray we are employing multiple patch antenna configurations with a variety of complex feeds and interconnection structures. Figure 4 below shows the initial design for the patch panel that is being used as a benchmark prototype for our E-textile designs. For the initial design, a corporate feed was chosen for implementation. One disadvantage of the corporate feed is that it occupies a large amount of real estate. This places a restriction on the possible variations in the design due to the need to minimize coupling and achieve a

desired element spacing. With larger corporate feeds, the loss increases more rapidly than for series-fed arrays, however, for small 2 by 2 arrays, the loss of a corporate feed is comparable to that of a series feed configuration. The corporate feed does offer a major advantage in that it simplifies the design by ensuring both the phase and amplitude of the patch excitations are all equal. Since the phase excitations of the elements are all the same with respect to frequency, the corporate feed helps to broaden the array's pattern bandwidth, i.e. helps to maintain the radiation pattern at frequencies off from the center frequency.
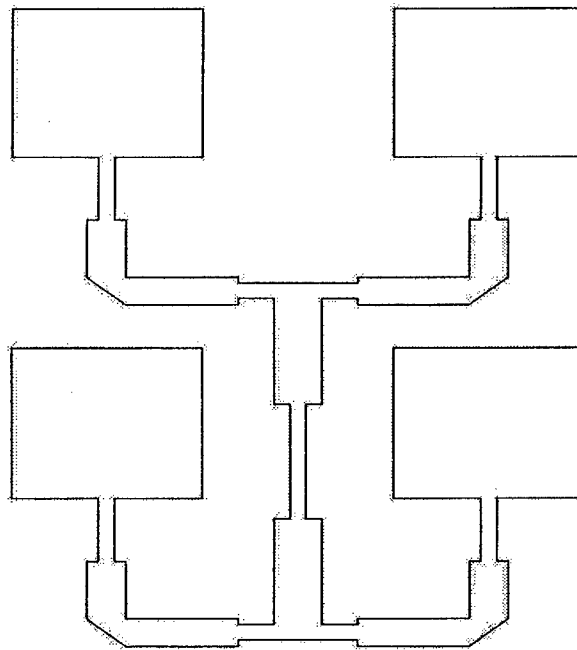

Figure 4: Microstrip E-Textile Patch Panel Layout

In constructing these subarray patch antennas, we are investigating a variety of existing textile materials. Among these are conductive fabrics that are typically used in shielding applications. One would expect that the price structure of such materials would be a function of the shielding effectiveness. Figure 5 below shows a plot of shielding vs. price for various conductive fabrics under consideration. The trend line indicates that the prices of materials increase as the shielding effectiveness increases. It should be noted that shielding is not the only factor that influences the cost of the material, which leads to the somewhat loose correlation.
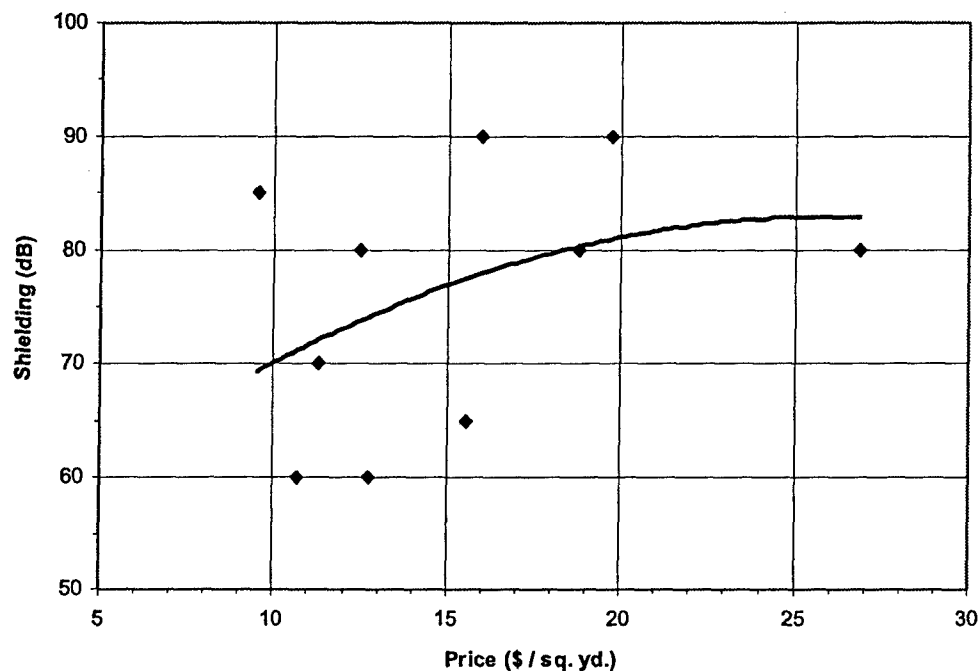
Figure 5: Shielding vs. Price of Various Conductive Fabrics

Shielding is not a critical property of the material when used in a planar antenna array. From a design viewpoint, loss is a major consideration among other properties in choosing a conductive layer. Figure 6 below shows a graph of loss vs. price for the same fabrics used in Figure 5.

It should be noted that the correlation has become even looser than in the previous case when shielding was the property of interest. The various fabrics appear to be grouped into two ranges of loss, one from approximately 160 to 190 dB / 100 meters and the other from 40 to 70 dB / 100 meters. The two groups are separated by approximately a factor of 3 on a dB scale. It should also be noted that the materials exhibiting lower loss have a trend line that is almost independent of price over the range shown. The designer is then left with several options: 1) a low-cost solution with high loss, 2) a high-cost solution with low loss, and 3) a low-cost solution with low loss. The materials of option 3 will be the first ones to be examined for the design.
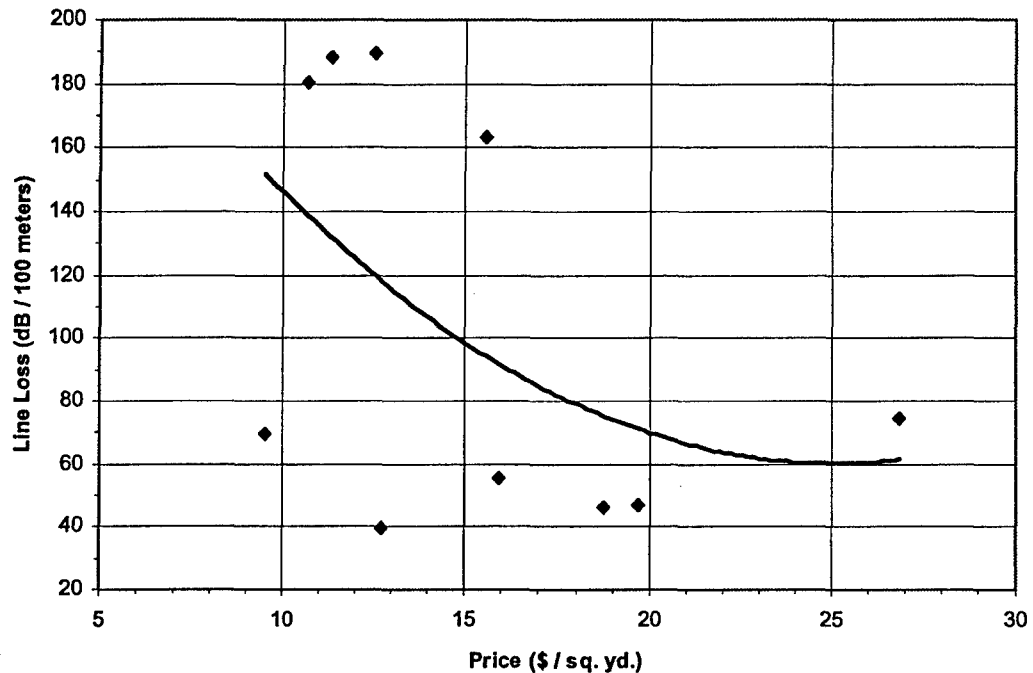
Figure 6: Loss vs. Price of Various Conductive Fabrics

It is important to estimate the performance of the quad patch panel using the characteristics of the textile materials from which it will be constructed. The two by two E-Textile patch panel array was modeled in computer simulation to predict its performance. Figure 7 below shows a plot of the input reflection coefficient. The goal for the center frequency of operation was 2.435 GHz, which is labeled as point 1 in Figure 2. Markers 2 and 3 show the bounding edges of the −10 dB impedance bandwidth of the array, which is approximately 6 % or 146 MHz. The predicted loss in the feed network was approximately 0.25 dB.

Figure 8 below shows the expected radiation pattern of the 2 by 2 array in both the E and H-Planes. As expected, the H-Plane pattern is symmetric while the E-Plane pattern is somewhat asymmetric due to the lines of physical symmetry along the E and H-Planes respectively. The half-power (-3 dB) beamwidth was approximately 28° in both planes. The predicted gain of the antenna was nearly 14.5 dB.

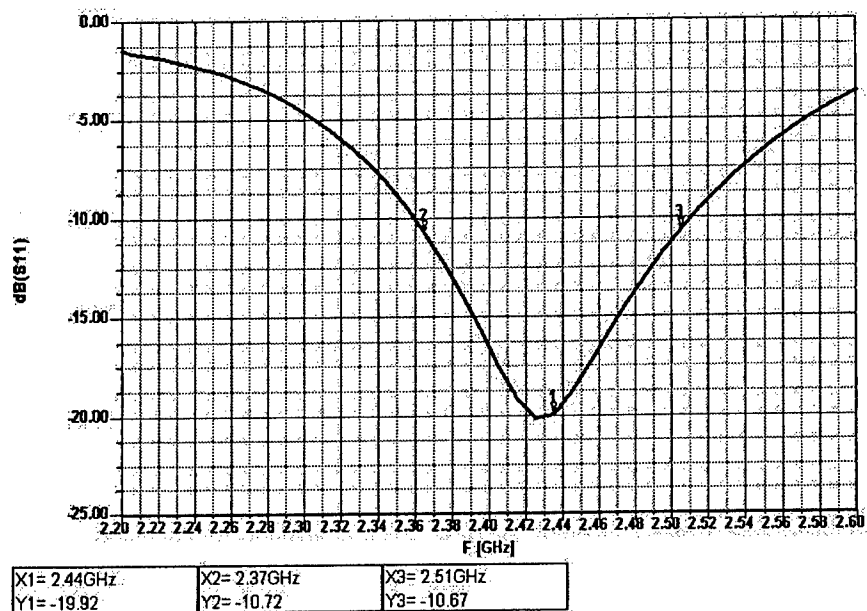| X1= 2.44GHz	X2= 2.37GHz	X3= 2.51GHz
Y1= -19.92	Y2= -10.72	Y3= -10.67

Figure 7: Predicted Input Reflection Coefficient of the 2 by 2 Patch Array
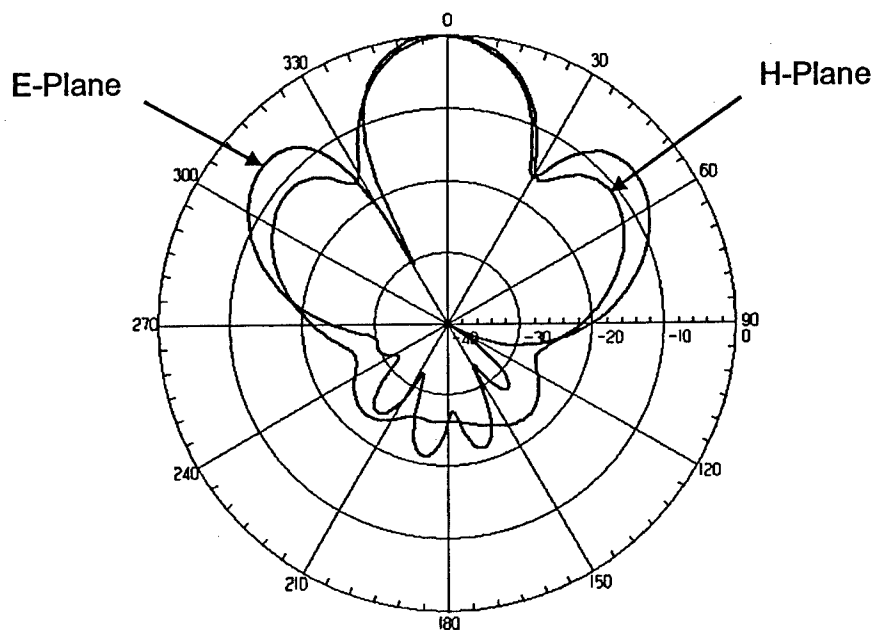

Figure 8: Predicted E and H-Plane Radiation Patterns of the 2 by 2 Patch Array

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5. Component Antenna Subarray Design

Once the 2 by 2 element subarray has been designed, larger arrays can follow by patterning the sub-array and connecting them together. Figure 9 below shows the layout of a square meter size panel of patches. The sub-arrays are connected together by a corporate feed on a lower trace layer behind a ground plane. Vias are used in order to connect the top trace layer that contains the patches to the bottom trace layer below the ground plane. The reason for using separate feed layers is to ensure that enough space will be available to construct the corporate feed that connects the sub-arrays together. The same procedure could be used to physically separate the four patches in the sub-array design from the corporate feed that connects them together, however, this would require an additional trace layer, and it would further complicate the manufacturing process.
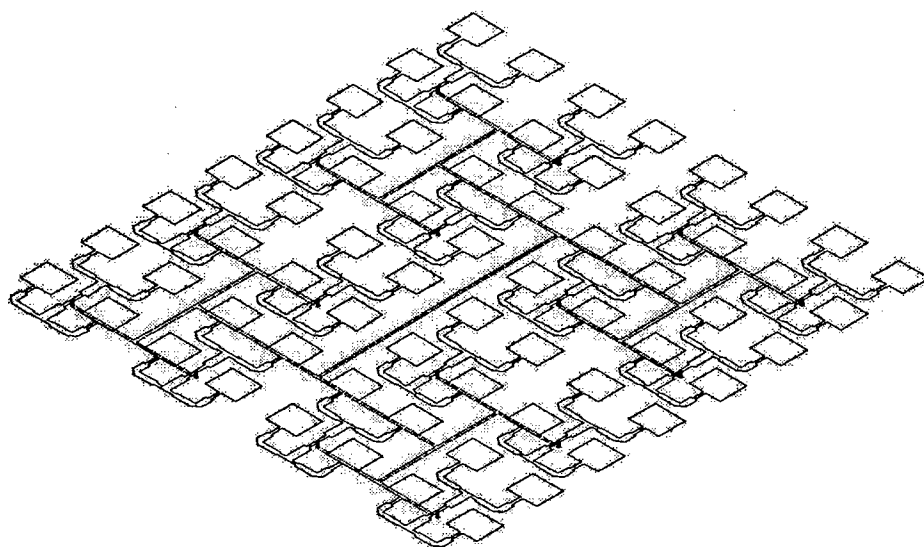

Figure 9: Initial Layout for a Square Meter Subarray of Patch Antennas

6. Summary

Investigations to date have shown that it is indeed possible to build one meter square E-Textile subarrays from which very large space-based arrays can be constructed. Significant challenges remain for the successful deployment of these arrays in space. Among these is to establish the textile construction method tolerances which in turn determine the maximum frequency at which this technology can be employed. The consistent reproducability of a uniform array product must also be demonstrated so that manufacturing yields with acceptable cost burdens can be realized. Finally, the best construction methods for individual satellite apertures must be established so that performance is maintained over the entire mission duration.

7. Acknowledgement:

8. References

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